The Cosmic Microwave Background Radiation Temperature at 30 GHz

Introduction

In this experiment we do a measurement first carried out in the late 1960s by Arno Penzias and Robert Wilson. We will measure the temperature of the afterglow from the big bang - the so called Cosmic Microwave Background Radiation. We do this by comparing the power of this emission with the emission from objects of known temperature. All objects emit "light" according to their temperature — but the emission from cooler objects occurs way down in the infra-red and microwave regions of the spectrum. Of course the fireball from the big bang was very hot but the Universe has expanded many times since then "stretching" the blinding white light way down into the microwave region. But it's still there filling the Universe - if we could see with microwave eyes we would see the sky glowing brightly. And "seeing with microwave eyes" is exactly what this experiment allows us to do.

A note on the Penzias and Wilson measurement can be found at: http://www.bell-labs.com/project/feature/archives/cosmology/

Measuring Temperatures with Thermal Radiation

We use the basic fact that at longer wavelengths, the power emitted by an object because of its heat is proportional to its temperature

$$P = \alpha T \tag{1}$$

where P is the power emitted, α is a constant that depends on area, wavelength, and other factors, and T is the temperature of the object in Kelvin. The key thing is to recognize that while it might be hard to get this factor α right, if you do nothing but change the temperature, the power change can be estimated.

We use this fact to measure the temperature of a remote object. Suppose we build an instrument that can measure the incoming radiation power and it has input optics arranged so that it "views" a small range of angles in front of the instrument. This is the basis of a radiometer. You can imagine this as a reverse flashlight. In the case of the flashlight, the filament of the light bulb is hot and emits through an arrangement of mirrors to form a narrow beam. For the radiometer, the "heat radiation" from a narrow range of angles funnels into the instrument and the power is detected and the amount of power read out on a meter.

To make a measurement of a remote object, we will determine the factor α by placing first an emitter of one known temperature in front of the radiometer, noting the power read on the meter, then placing a different emitter with a different known temperature in front of the radiometer and noting the new power level.

$$\alpha = \frac{P_1 - P_2}{T_1 - T_2} \tag{2}$$

There is one further complication. The radiometer itself is not perfect and the amplifier inside has some 'noise' which generates some power of it's own. So even if we pointed the radiometer at an object with $T = 0$ there would be some power. This extra power is denoted in terms of the temperature you would measure if you looked at a zero temperature emitter and did not correct for this fact. We therefore correct equation 1 to read

$$P = \alpha(T + T_{\mathrm{rx}}) \tag{3}$$

We can solve for T_{rx} from the two known temperature emitters we used to find α

$$T_{\mathrm{rx}} = \frac{P_1}{\alpha} - T_1 \tag{4}$$

With these two constants measured, we can 'point' the radiometer anywhere and remotely measure the temperature of anything by rewriting equation 3 and using our knowledge of α and T_{rx}.

$$T = \frac{P}{\alpha} - T_{\mathrm{rx}} \tag{5}$$

Measuring the Temperature of Items in the Lab

During the first week of the lab we will measure the temperature of several items using the radiometer.

Some things you could measure:

1. The wall
2. The sky through the door of the lab
3. Your face

For each item, you will need to make three measurements quickly in succession. The cold load, the hot load, and the unknown. The hot load is a piece of material that is a good emitter which is at a temperature near room temperature (measured with a thermometer). The cold load is a similar material that is dipped in liquid Nitrogen and placed in front of the radiometer. Then comes the unknown. For each of these objects you will need to read the power reading on the power meter attached to the radiometer.

Find the unknown temperature using equation 2 to find α, equation 4 to find T_{rx}, with T_1 and P_1 being the temperature and power for the hot load, T_2 and P_2 being the temperature and power for the cold load. Then using equation 5, find the unknown temperature using the power measured while the unknown was in front of the radiometer.

Measuring the Temperature of the CMB

Measuring the temperature of the CMB is conceptually the same as measuring the temperature of the items in the lab. We will compare the power we get from the sky to the hot and cold loads.

Because the temperature is very low (just a few degrees K) we have to take a more careful account of a few things than we did for the previous section. First, we will have to get T_{rx} pretty accurately because the CMB temperature, T_{CMB} is less than T_{rx}. Second because the CMB is such a small signal we need to worry about other contributions to the power we measure when the receiver is pointed at the sky. We will worry about two factors.

The first is the comparatively hot ground and buildings around us. We will investigate this by placing a ground shield on the radiometer which keeps the ground emission out of the input. We will check how much difference this makes and subtract that source if it seems to be an important factor.

The second, and more difficult extraneous contribution to remove is emission from our own atmosphere. While the atmosphere is almost transparent (and non-emissive) it is not perfect. What's more, the main emitter is water-vapor which varies a lot. There is not much water vapor on those clear, crisp days when the sky is deep blue. On the other hand, when it's wet and cloudy, there is a lot of water vapor, and consequently, if we point our radiometer up at the sky we will get a hotter temperature on humid or wet days.

How can we estimate the amount of power coming from the atmosphere when we point the radiometer at the sky? We need to do this to get a good estimate of T_{CMB}. We do this by measuring the effective temperature at a variety of angles from the vertical. We can calculate how much atmosphere we are going through for each angle and from that, extrapolate the temperature we would get if were looking through zero atmosphere. The atmosphere contribution approximately follows

$$T_{\text{atm}}(z) = T_0 A(z) \tag{6}$$

where $A(z)$ is the number of airmasses you are looking through. $A(z) = \sec(z)$ and is equal to 1 when looking straight up ($z = 0$). T_0 is the effective atmospheric temperature at the zenith and z is zenith angle (the angle between straight up and where the radiometer is looking). The total temperature we will measure when looking at the sky will be

$$T_{\text{total}} = T_{\text{CMB}} + T_{\text{atm}}(z) + T_{\text{rx}} \tag{7}$$

To get an estimate of T_0, we will measure the T_{total} at a variety of zenith angles. We then plot $T_{\text{total}} - T_{\text{rx}}$ vs $A(z)$ to get a straight line for $A(z)$ going from 1 to about 2 (z going from 0 to 60°). Then we can extrapolate the straight line to $A = 0$ and read off T_{CMB}.